Simulation of relativistic shocks and associated radiation from turbulent magnetic fields

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Recent PIC simulations of relativistic electron- positron (electron- ion) jets injected into a stationary medium show that particle acceleration occurs at shocked regions. Simulations show that the Weibel instability is responsible for generating and amplifying highly nonuniform, small-scale magnetic fields and particle acceleration. These magnetic fields contribute to the electron's transverse deflection behind the shock. The ``jitter'' radiation from deflected electrons in turbulent magnetic fields has different properties than synchrotron radiation, which is calculated in a uniform magnetic field. This jitter radiation may be important for understanding the complex time evolution and/or spectral structure in gamma-ray bursts, relativistic jets in general, and supernova remnants. New spectra based on small scale simulations will be presented.

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Plasma instabilities (e.g., Buneman, Weibel and other two-stream instabilities) excited in collisionless shocks are responsible for particle (electron, positron, and ion) acceleration. Using a new 3-D relativistic particle-in-cell code, we have investigated the particle acceleration and shock structure associated with an unmagnetized relativistic electron-positron jet propagating into an unmagnetized electron-positron plasma. The simulation has been performed using a long simulation system in order to study the nonlinear stages of the Weibel instability, the particle acceleration mechanism, and the shock structure. Cold jet electrons are thermalized and slowed while the ambient electrons are swept up to create a partially developed hydrodynamic (HD) like shock structure. In the leading shock, electron density increases by a factor of ≤ 3.5 in the simulation frame. Strong electromagnetic fields are generated in the trailing shock and provide an emission site. We discuss the possible implication of our simulation results within the AGN and GRB context. We have calculated the time evolution of the spectrum from two electrons propagating in a uniform parallel magnetic field to verify the technique. The same technique will be used to calculate radiation from accelerated electrons (positrons) in turbulent magnetic fields generated by Weibel instability.

We have performed 3-D simulations injecting an electron-positron jet into electron-positron ambient plasma (Nishikawa et al. 2009b). This computational domain is six times longer than in our previous simulations (Nishikawa et al. 2006; Ramirez-Ruiz, Nishikawa & Hededal 2007). The jet-electron number density in the simulation reference frame is $0.676n_a$, where n_a is the ambient electron density, and the jet Lorentz factor is $\gamma_j = 15$.

Figure 1a & b show the averaged (in the $y - z$ plane) (a) jet (red), ambient (blue), and total (black) electron density and (b) electromagnetic field energy divided by the total jet kinetic energy at $t = 3250\ \omega_{pe}^{-1}$. Positron density profiles are similar to electron profiles. Ambient particles become swept up after jet electrons pass $x/\Delta = 500$. By $t = 3250\ \omega_{pe}^{-1}$, the density has evolved into a two-step plateau behind the jet front. The maximum density in this shocked region is about three times the initial ambient density. The jet-particle density remains nearly constant up to near the jet front.

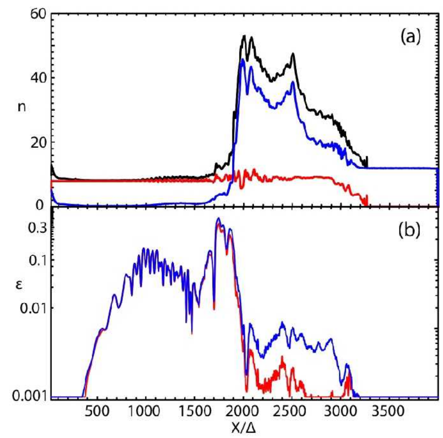

Fig. 1- Averaged values of (a): jet (red), ambient (blue), and total (black) electron density, and (b): electric (red) and magnetic (blue) field energy divided by the jet kinetic energy at t = 3250 ω_{pe}^{-1}.

We have calculated radiation from two electrons propagating along the uniform magnetic field toward an observer (Nishikawa et al. 2009a).

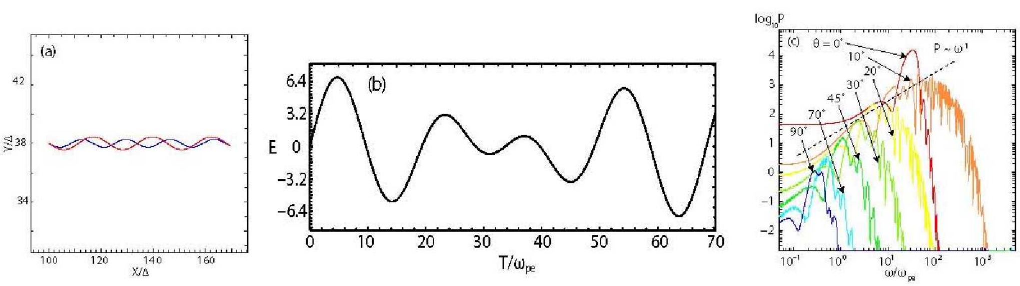

Fig. 2 – The paths of two electrons moving helically along the x–direction in a homogenous magnetic (Bx) field shown in the x–y-plane (a). The two electrons radiate a time dependent electric field. An observer situated at great distance along the n-vector sees the retarded electric field from the moving electrons (b). The observed power spectrum at different viewing angles from the two electrons (c). Frequency is in units of ω_{pe}^{-1}.

Emission obtained with the method described above is self-consistent, and automatically accounts for magnetic field structures on the small scales responsible for jitter emission. By performing such calculations for simulations with different parameters, we can investigate and compare the quite different regimes of jitter- and synchrotron type emission (Medvedev 2006). The feasibility of this approach has already been demonstrated (Hededal 2005, Hededal & Nordlund 2005), and its implementation is straightforward.

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